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LONG-TERM VARIATIONS IN EQUATORIAL CIRCULATION AND RAINFALL

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ABSTRACT

The large-scale air-sea interaction over the equatorial Pacific proposed by Bjerknes is investigated. It was found from a study of the Canton Island record that ocean temperature, rainfall, trade wind flow, and equivalent potential temperature are related and undergo long-term variations with periods in excess of a year. Similar changes occur in the high troposphere.

Satellite cloud observations, however, indicate important longitudinal variations near the Equator. During the abnormal rainy season of 1965–66 at Canton Island, the amount of cloudiness remained low over the eastern equatorial Pacific despite above-normal sea-surface temperatures. This suggests a continuation of the widespread subsidence usually present over this region, which is apparently part of a large-scale semipermanent zonal circulation.

Satellite observations further show that there are three major "centers of action" (standing eddies) in the vicinity of the Equator. Probably the major part of the condenstion heating necessary for the Hadley circulation occurs in these areas.

This study also indicates a possible relation between equatorial rainfall in the central Pacific and the strength of the Northern Hemisphere westerlies as suggested by Bjerknes. In addition, rainfall appears to vary inversely with the eddy kinetic energy over the Northern Hemisphere suggesting an inverse relation with the large-scale planetary waves in the Northern Hemisphere.

1. INTRODUCTION

In a provocative article, Bjerknes (1966) has described an air-sea interaction in the Tropics that may regulate the intensity and distribution of tropical rainfall and in turn may influence midlatitude circulations. His hypothesis is that when equatorial ocean temperatures are warmer than average an increase in convective rains occurs and consequently a greater release of latent heat. This heating accelerates the meridionally circulating Hadley cell causing a greater export of heat and momentum to middle latitudes, leading in turn to stronger zonal westerlies.

As Bjerknes has indicated, the eastern equatorial Pacific is a particularly promising region for the study of such an air-sea interaction. Here, temperatures in the westward flowing equatorial current are normally several degrees colder than those occurring 10° north and south. This relative coldness is believed primarily due to upwelling rather than advection of cold water from the northward-flowing Peru Current. Estimates of the intensity of this upwelling by Ichiye (1966) indicate it to be of the order of 10^{-3} to 10^{-2} cm sec^{-1} or a maximum of about 8 m per day; and since the water temperature above the thermocline drops about 5°C per 50 m, this is equivalent to a surface cooling of roughly 0.5°C per day.

Coinciding with this tongue of relatively cool subsurface water along the Equator is the well-known "Pacific dry zone." This zone is very conspicuous on maps of global cloudiness obtained from a summarization of meteorological satellite observations (Taylor and Winston, 1968; Winston, 1967). Two examples are shown in figure 6, but these will be discussed later in this paper. Within this zone, from about 165° W. longitude to the South American coast, rainfall averages less than 30 in. per year and is highly variable. Northward and southward it increases, reaching a maximum approximately where ocean temperatures are also a maximum. This spatial correlation between cloudiness, rainfall, and sea-surface temperatures suggests that the colder upwelled water along the Equator strongly suppresses rainfall by cooling and stabilizing the air near the surface. This interpretation has been questioned, however, since it does not explain the dry inversion that overlies this area. Riehl (1954) has pointed out that this inversion cannot be explained by surface cooling, but rather by widespread subsidence with low-level horizontal divergence. From a study of climatic data obtained from the Line Islands, Sadler (1959) has prepared surface streamlines depicting this equatorial divergence.

The upwelling of equatorial water in the eastern Pacific is considered to result from an Ekman divergence due to the wind stress exerted by these subsiding trades. Consequently, it should vary with the strength of these winds: strong trades giving upwelling and colder water, weak trades resulting in reduced upwelling and warmer ocean temperatures. The warmer ocean temperatures in turn should then be accompanied by increased cloudiness and rainfall as Bjerknes has suggested.

If sufficient meteorological and oceanographic observations were available, it would be fairly simple to verify the above hypothesis. Unfortunately this is not the case; and, consequently, one is forced to depend in part upon an analysis of time series of temperature and rainfall for a few representative stations. A very limited number of commercial ships do provide some conventional meteorological data as well as sea-surface temperature measurements.

Meteorological satellites are now beginning to add substantially to our information about the equatorial

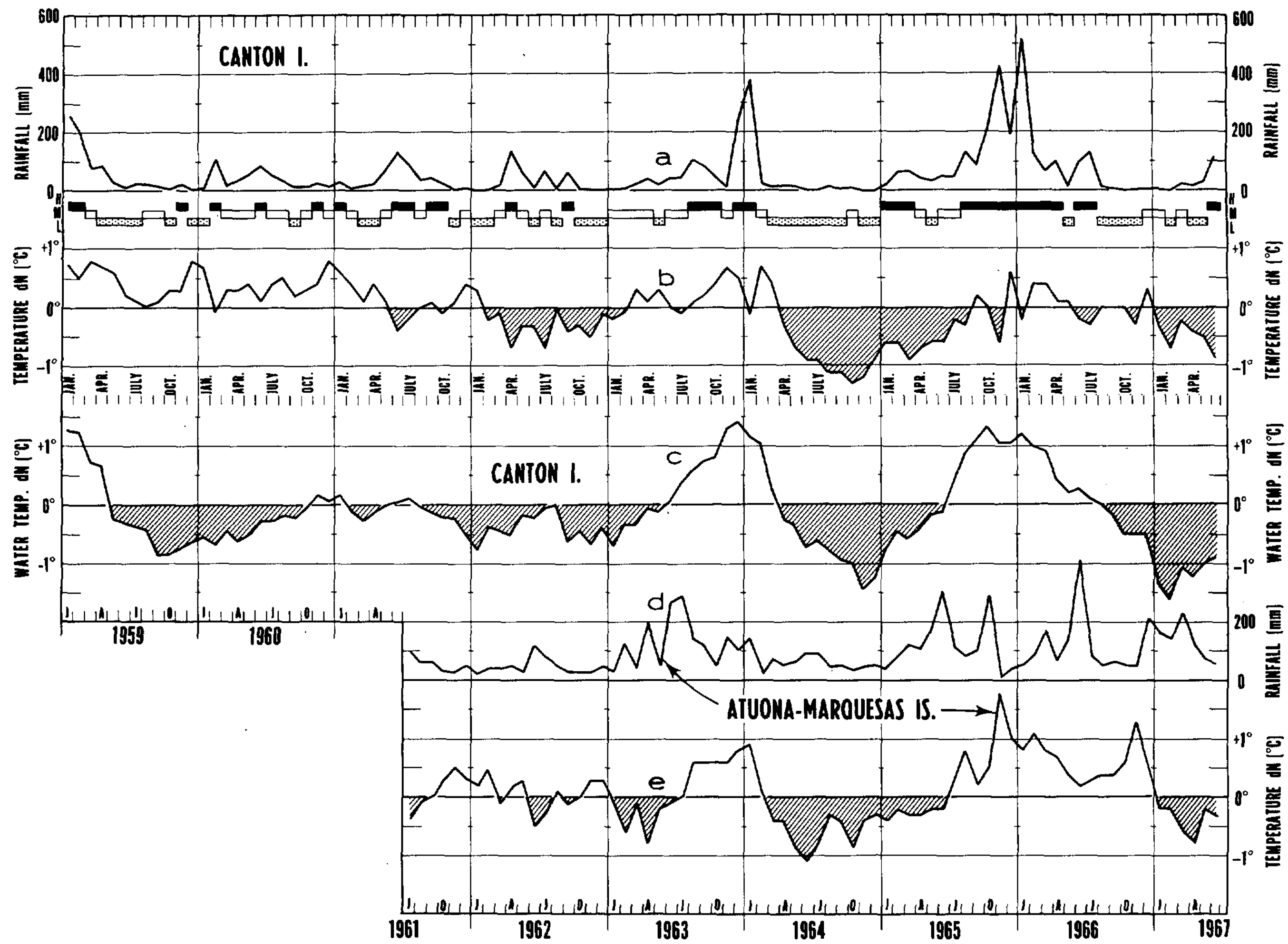

Figure 1.—Time series of monthly (a) rainfall, (b) surface air, and (c) sea-surface temperature anomalies for Canton Island; (d) rainfall and (e) surface temperature anomaly for the Marquesas Islands. Tercile classification of Canton Island rainfall is indicated by rectangles below (a).

Pacific since the advent of nearly global video observations of the earth in the middle 1960's. Thus, it is now possible to study variations in cloudiness over the tropical Pacific and in turn attempt to relate these to circulation changes implied by the limited amount of conventional data. This essentially outlines what we have attempted to do in this report. More recently, in a study that parallels ours, Bjerknes has extended his investigation of this air-sea interaction to the 1960's and has published further results in another stimulating paper (Bjerknes, 1969).

2. AIR-SEA FLUCTUATIONS OVER THE EQUATORIAL PACIFIC

THE CANTON ISLAND RECORD

A convenient place to begin is with a consideration of rainfall and temperature at Canton Island (2°46′ S., 171°43′ W.) which is located at the western edge of the equatorial dry zone. A time series of these quantities is shown in figure 1. These data, as well as most of the meteorological averages presented in this paper, were obtained from climatic data published by the U.S. Weather Bureau and Environmental Data Service (1959–1967). Sea-surface temperatures for Canton Island, on the other hand, were furnished by the U.S. Coast and Geodetic Survey (1969). In this figure, the upper curve is monthly rainfall, the next is the monthly average air temperature anomaly, and the third is the ocean temperature anomaly. Particularly striking is the parallel long-period variation in rainfall and temperature (both sea and air) since 1963. Superimposed, however, are shorter period fluctuations of the order of several months for which rainfall and air temperature (and to a slightly lesser extent sea temperature) are out of phase. This is particularly noticeable during the periods of heavy rains that occurred during 1963–64 and again during 1965–66. Of interest is the correlation (based upon 18 yr of observations at Canton Island of 0.66 between monthly averages of ocean and air temperatures. Nonoverlapping yearly averages, however, have a correlation of 0.78 and suggest the presence of low-frequency oscillations with periods of more than 1 yr in the vicinity of the Equator. Since 1963 these fluctuations, particularly in sea-surface temperature, have fairly large amplitudes and appear to be approximately 2 yr apart. For 2 or 3 yr prior to this, however, such a periodicity was not readily apparent in both ocean and air temperatures.

Bjerknes' figure 1 (1969) indicates that the heaviest rains occurred at Canton Island when the water temperature exceeded the air temperature and was greater than 29°C. Conversely, when the ocean surface was colder than 28°C and less than the air temperature, rainfall was often negligible. In view of these relationships there are apparently some important long-period fluctuations in the energy exchange between the ocean and atmosphere in the equatorial Pacific.

The small, but significant air-mass changes that occur in the lower troposphere and accompany these surface temperature variations are also of interest. An example of this is shown in figure 2. Here, the vertical temperature and dew-point distribution at Canton Island for January 1966 is compared with that for January 1967. As figure 1 indicates, January 1966 was a month of very heavy rainfall (520 mm), while during January 1967 rainfall was very scant (7 mm). Although the temperatures for these 2 mo differed only slightly, figure 2 indicates that the vertical stability below 700 mb was greater during January 1967. The presence of the trade wind inversion, which is accompanied by lower humidities, is probably typical of average conditions over the equatorial Pacific. By comparison, the lower troposphere during January 1966 appears very anomalous. At 700 mb, for example, the dew point was nearly 10°C higher than in 1967, while at the surface it was 2.6°C higher. This surface difference is especially important since it indicates that the equivalent potential temperature in January 1966 was 10°C higher than that which occurred 1 yr later. This in turn indicates that the convective condensation level and the level of free convection were lower in January 1966 than in January 1967. As a consequence, convective motions initiated from the surface in January 1966 would become buoyant at 900 mb and in turn would continue freely from here at an equivalent potential temperature of about 355°K to the tropopause. In contrast, during the following January, it would be necessary to lift the surface air to 680 mb for it to become buoyant—this time at a value of $\theta_E=345$°K. Entrainment would further reduce this buoyancy and require a greater expenditure of energy from the environment. Probably because of the horizontally uniform temperatures and low wind speeds usually occurring near the Equator, sufficient energy is seldom available for this amount of work. This may partially explain why rainfall is not as plentiful in the dry zone when the surface temperature and humidity are only slightly lower.

With a favorable temperature and humidity distribution, energy-producing convective motions can only occur in the Tropics if the upward motion originated near the surface. This condition has been emphasized by Riehl (1954) and Gray (1967) and is shown graphically in figure 3. In this figure the January 1966 vertical temperature distribution for Canton Island is again presented. In addition, the moist adiabatic process that would result from ascent originating at the specified levels is also indicated. Notice that for moist convection originating from levels above the 960-mb level the upward-moving air remains colder than its environment. Only vertical motion originating from convergence below the 960-mb level can produce tropospheric warming. Thus, not only are the low-level temperature and humidity important, but also the convergence pattern in this lowest 100-mb layer.

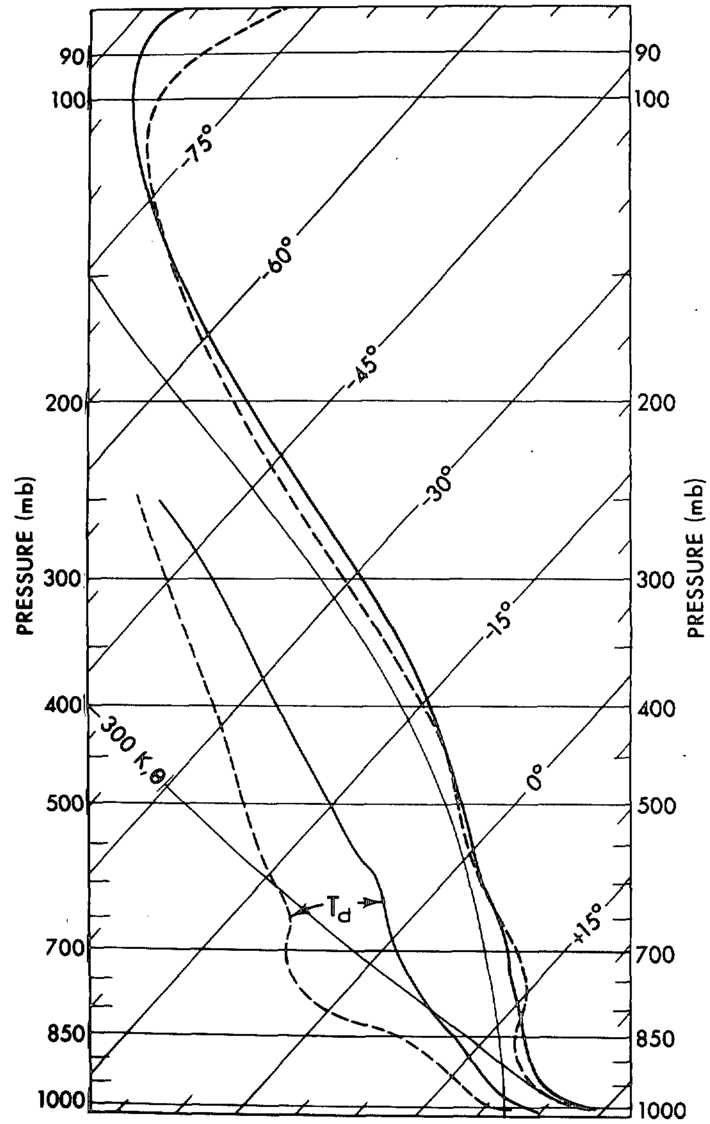

FIGURE 2.—Monthly mean temperature and dew point versus pressure at Canton Island for January 1966 (solid) and 1967 (dashed). Diagram is skew-T, log p.

Since the surface air temperature and humidity appear to play an important role in regulating the varying precipitation regimes, it is useful to examine a time series of monthly average surface equivalent potential temperatures (θ_E). This is shown for Canton Island for the period from January 1964 to 1967 in figure 4. For comparison the corresponding portion of figure 1 has been repeated in the

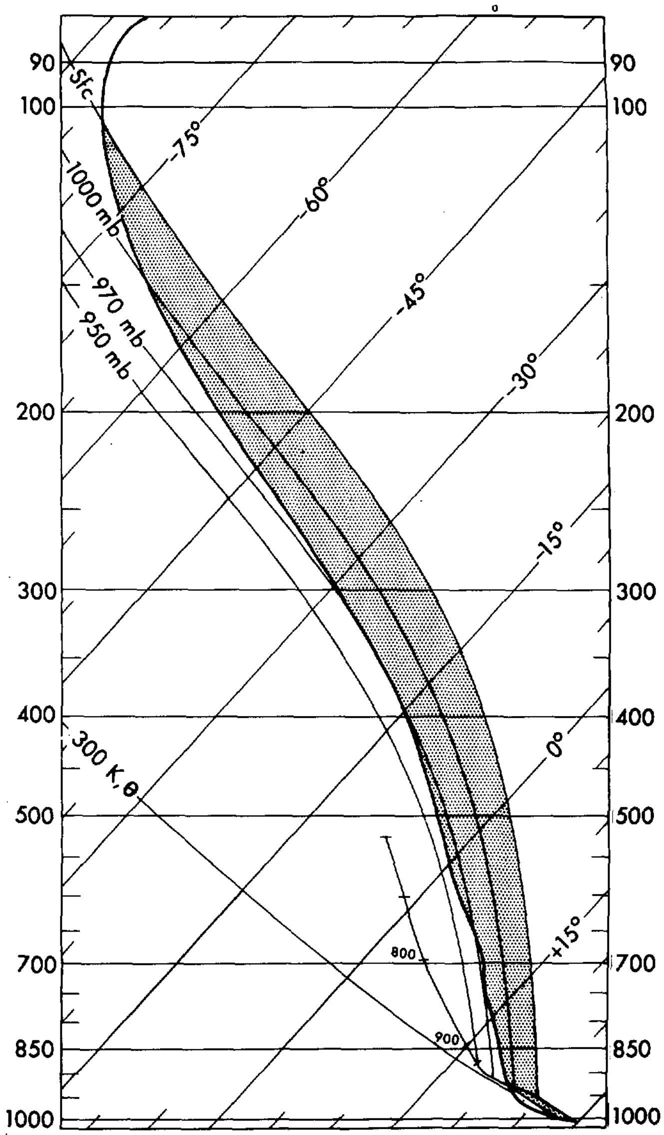

FIGURE 3.—Repeat of January 1966 temperature sounding for Canton Island. Numbers at upper left portion of figure represent moist adiabatic ascent beginning at pressure levels indicated. Note that for parcel ascent from levels higher than the 950-mb level the air parcel remains cooler than its environment.

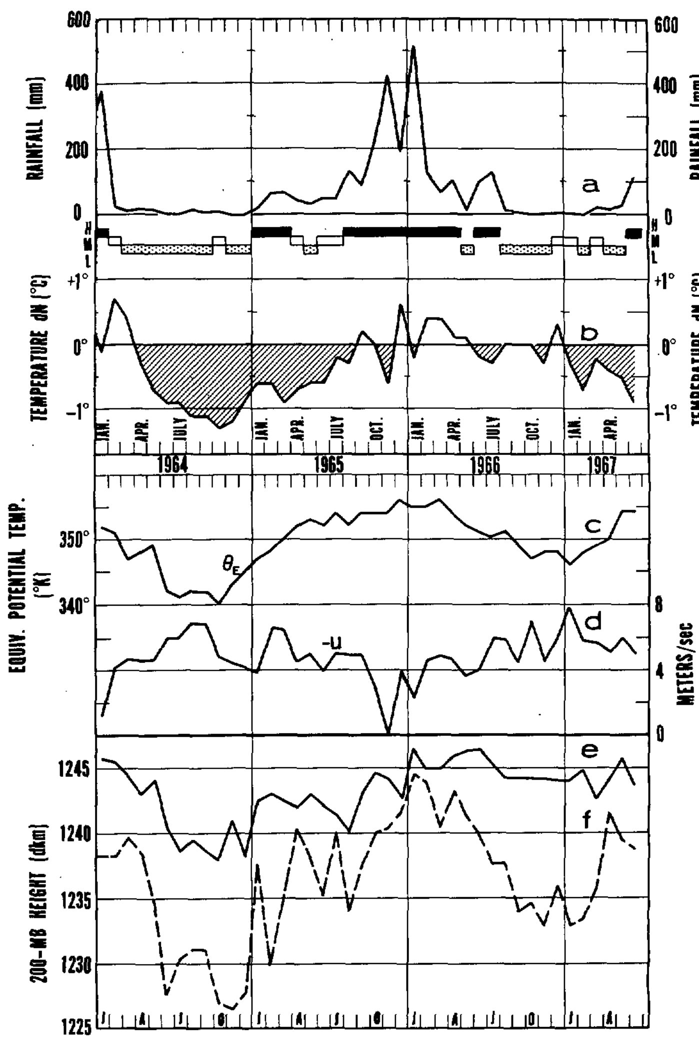

FIGURE 4.—Canton Island time series from January 1964 of (a) rainfall, (b) air temperature anomaly, (c) surface equivalent potential temperature (θ_E), (d) monthly surface easterly wind component ($-u$), (e) monthly mean 200-mb heights. Curve (f) is the 200-mb heights for Tahiti.

upper part of this figure. The values of θ_E display the same parallel long-term variation as ocean temperature and rainfall. It was as low as 340°K during the prolonged drought in 1964–65 and rose to 356°K during the copious rains of 1965–66.

It was indicated that fluctuations in the trade winds are important in regulating the equatorial upwelling and consequently the sea-surface temperatures. The previous discussion suggests that the sea-surface temperatures in turn regulate the surface equivalent potential temperature and consequently the condensation level as well as the level of free convection. It would, therefore, be useful also to examine a time series of surface wind speeds in the Pacific dry zone. Monthly resultant winds were available only from the once-a-day rawinsonde observations at Canton Island, and from these we have determined the surface easterly wind component ($-u$) and plotted these also in figure 4. The variation indicated is the expected one and is inverse to temperature and rainfall. During periods of low temperature and rainfall, the easterlies averaged about 7–8 m sec^{-1}, while during periods of higher temperatures and rainfall they were less than 4 m sec^{-1}.

A relation between wind and rainfall in the Pacific dry zone is not new and has been noted by Brooks (1926) and Seelye (1950). In particular, Brooks found a relation between wind direction and steadiness and rainfall. At Malden Island (4° S., 155° W.) he noted that when the wind constancy was high, rainfall was low; and when constancy was low, rainfall was high. The correlation between the two was found to be -0.73. Resultant winds of high constancy were predominantly from the east, while occurrences of low wind constancy consisted of a sharply reduced number of east winds and more flow from other directions, particularly northeast. He suggested that low constancy indicated an eddying motion in the equatorial circulation. The greater prevalence of northeasterly winds during the rare rainy periods also suggests more Northern Hemisphere air south of the Equator.

LARGE-SCALE CHANGES OVER THE EQUATORIAL PACIFIC

We have examined the climatic record for Canton Island in considerable detail because until August 1967 it was the only equatorial meteorological station in the central Pacific (now there are none). It will be useful now to consider the spatial as well as temporal variations in ocean temperature and cloudiness.

Figure 5 shows the year-to-year variation of seasonally averaged sea-surface temperature anomalies for the eastern tropical Pacific. Note that these anomalies are in degrees Fahrenheit. Each map is an average for the months of December, January, and February and was obtained from data gathered by the Bureau of Commercial Fisheries (Renner, 1962–1967). The maps should be considered as approximate because the data available in parts of the Pacific are limited to only a very few observations per month.

For these 5 yr at least, these maps indicate that sea-surface temperatures at Canton Island were fairly representative of water temperatures over most of the equatorial Pacific. In particular the 1965–66 season was indicated as being unusually warm along the Equator. Also of interest was the tendency since the end of 1962 for these anomalies to alternate from year to year.

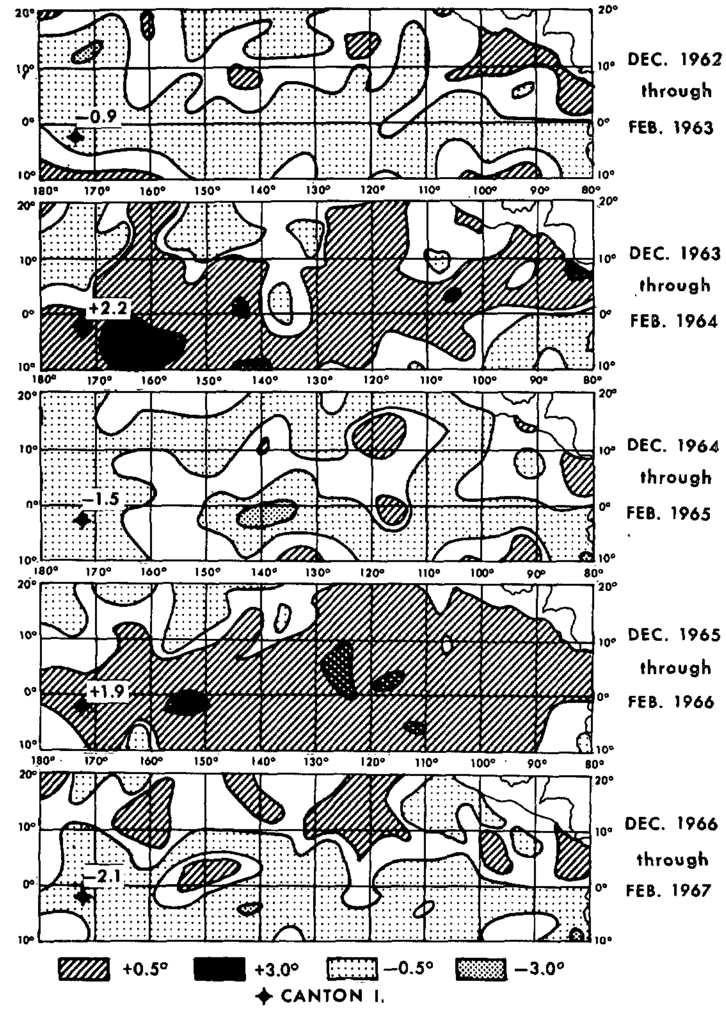

FIGURE 5.—Seasonal mean sea-surface temperature anomalies for the eastern equatorial Pacific for the five winter (Northern Hemisphere) seasons from December 1962–January 1967. Note that the temperature anomaly is expressed in degrees Fahrenheit.

Corresponding data for cloudiness were available for January 1966 and 1967 and are shown in figure 6. The map for January 1966 is based upon observations obtained from TIROS IX and X. It is a monthly mean obtained from subjective estimates of cloudiness made from individual photographs for each day. On the other hand, the map for January 1967 is obtained from observations from ESSA 3 and in addition, it should be noted, is based upon a computer-processing of individual daily brightness values. Since the process is described elsewhere, it will not be discussed here (see Taylor and Winston, 1968). Because the maps were obtained by two different methods, only a qualitative comparison should be made. For this reason the isopleths are not labeled.

South of the Equator, the major cloudiness in January 1966 was located farther northeast towards Canton Island and Samoa, as compared with January 1967. In 1967, Canton Island appears to be very definitely in the dry zone. The most interesting characteristic of these two cloudiness maps is their similarity, particularly with regard to the large area of little cloudiness over most of the equatorial Pacific. Thus January 1966, despite its anomalously warm ocean temperatures, did not display any major increase in cloudiness (and hence rainfall) except in the southwestern part of the region in the vicinity of Canton Island. Apparently the relation between rainfall and ocean temperature anomaly noted for Canton Island does not necessarily hold farther east in the Pacific dry zone. It should be noted, however, that an ocean temperature anomaly of +3°F (+1.7°C), as observed at the Equator near longitude 125° W., represents a temperature of about 26°C as compared with the 29°C observed at Canton Island. With a relative humidity of say 75 percent, this represents a surface value for θ_E of 345°K, which is probably too low for buoyant convection in the Tropics.

Even under more favorable conditions, however, rainfall may not necessarily occur in phase with temperature. Consider the time series of rainfall and air temperature anomaly of Atuona in the Marquesas Islands (9°49′ S., 139°01′ W.) shown at the bottom of figure 1. Notice in particular the inverse variation of rainfall in the Marquesas as compared with that for Canton Island during 1965–66. During this same period the air temperature in the Marquesas was as much as 1.8°C above normal, and the ocean anomaly was +0.8°C, representing a temperature of

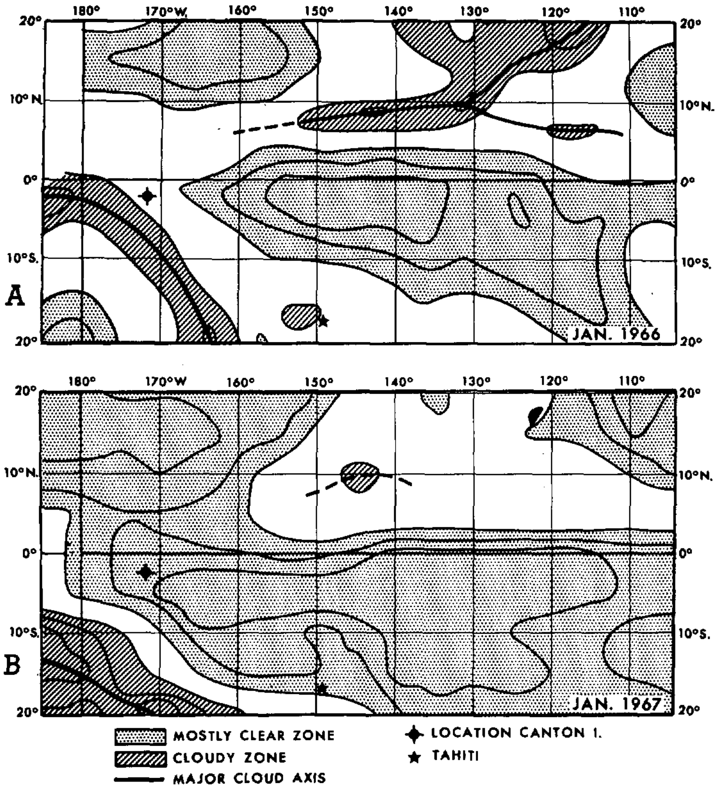

FIGURE 6.—Satellite observations of monthly mean cloudiness for the eastern Pacific for January 1966 (A) and January 1967 (B). Data for January 1966 were obtained from a subjective evaluation of cloudiness from TIROS IX and TIROS X photography; data for January 1967 are based upon computer-processed daily brightness observations from ESSA 3.

28°C. Probably the Marquesas, despite the surrounding warm ocean, were located under the descending branch of the circulation responsible for the heavy rains at Canton Island. Once this circulation retrograded and the rains at Canton Island diminished, they again broke out in the Marquesas.

The surface center of this circulation in January 1966 was located over Samoa where pressures averaged slightly less than 1005 mb (fig. 7). Over Australia, Indonesia, and New Guinea, pressures were somewhat higher when compared with both 1965 and 1967, reflecting a weaker summer monsoonal circulation in those areas in 1966. During January 1967 (fig. 7), the pressure in the vicinity of Samoa was 5 mb higher as the Low this time was centered about 40° farther west in the vicinity of the Solomon Islands—a location closer to its normal position.

Associated with the monthly mean low-pressure center in the vicinity of Samoa during January 1966 were temperatures around 28°C and relative humidities as high as 86 percent. Since these also indicate high values for the surface equivalent potential temperature (θ_E), which we have seen varies with the ocean surface temperature in the Tropics, it is of some interest to map the distribution of θ_E over the equatorial Pacific. A quantity similar to θ_E and easier to obtain is the isobaric equivalent temperature. It is computed from

$$T_E = T + \frac{L}{c_p} q$$

where T is the temperature, q the specific humidity, L the latent heat of condensation, and c_p the specific heat at constant pressure. The quantity T_E can readily be obtained graphically or by slide rule from surface temperatures and humidities. Note that $c_p T_E$ is the surface value of $Q = c_p T + gz + Lq$, a quantity like θ_E that is conserved during moist adiabatic processes. Thus the value of $T_E = 75°C$, coincident with the Low in the central Pacific in figure 8, is equivalent to $Q_0 = 83.5$ cal gm^{-1} and is comparable to the value that Riehl and Malkus (1958) found in the equatorial trough zone. A value for T_E greater than 70°C appears necessary for buoyant convection. One year later, T_E dropped over most of the equatorial Pacific, and values of $T_E = 75°C$ were now located farther west along the northwest and northeast coasts of Australia as well as along the dateline at latitude 10° S. These changes as well as the rises in subtropical latitudes both north and south suggest a widespread weakening of the equatorial trough zone in 1967 (fig. 8).

3. CIRCULATION IN THE UPPER TROPOSPHERE

The surface temperature fluctuations we have been describing were accompanied by parallel changes in temperature and geopotential in the upper troposphere. Consider, for example, the variations in 200-mb heights at Canton Island and also Tahiti shown in figure 4. While there are fluctuations of the order of several months, there is also a long-period oscillation readily apparent—particularly at Tahiti—which is in phase with the corresponding fluctuations in temperature, θ_E, and rainfall at Canton Island.

This suggests that the monthly mean low-pressure area near Samoa in January 1966 (fig. 7) was warm, particularly in the upper troposphere and was capped by an anticyclonic circulation. Figure 9, which shows the monthly average thickness between 500 and 100 mb and also the corresponding 100-mb surface, indicates this type of circulation. Admittedly, the amount of data that these analyses are based upon is extremely limited; and they should, therefore, be considered as approximate. However, anticyclonic circulation for the upper troposphere is indicated from the resultant winds and vertical wind shear at Nandi, Tahiti, and Canton Island.

The coincidence of this high-level warm anticyclone with heavy rains and high values of T_E (fig. 8) over much of the area surrounding Samoa suggests that condensation heating contributed to its formation. This type of circulation was first described by Riehl (1959), who pointed out that these warm Highs are associated with an energy-producing mass circulation. Inflow and convergence of

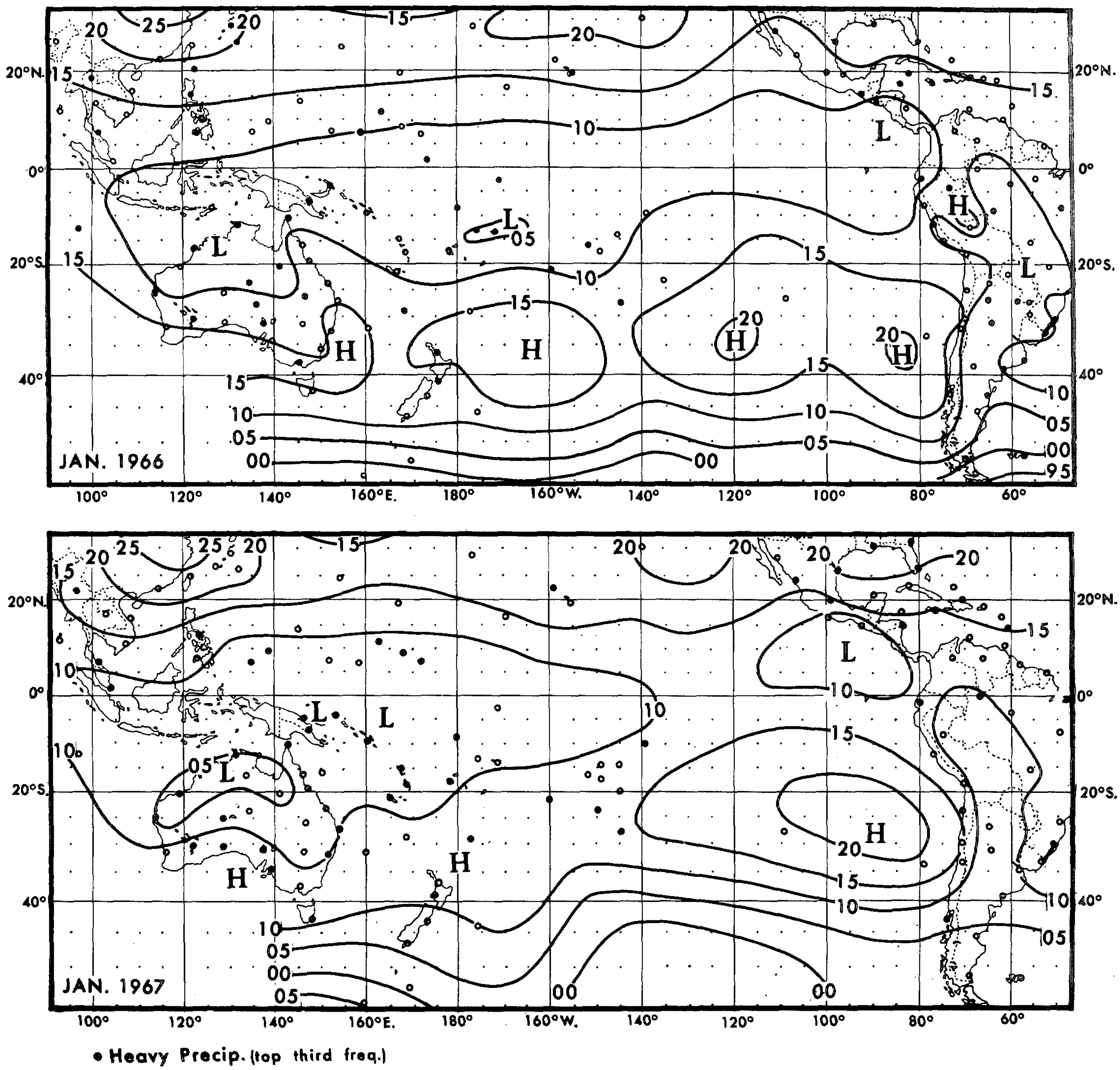

FIGURE 7.—Monthly mean sea level pressure for the central Pacific for January 1966 and January 1967.

water vapor occur near the surface, and outflow and divergence of heat occur near the top. Calculations carried out by Rosenthal (1967) with a two-level, linear, quasi-geostrophic model suggest that convective heating produced from convergence in the Ekman layer can lead to a simultaneous growth of perturbations in the upper and lower troposphere that have horizontal scales of the order of several thousand kilometers.

The most favorable location for this convective heating is probably where the Ekman boundary convergence occurs with high values of T_E (hence θ_E) since this requires the least amount of lift to the level of free convection. Thus, the ocean surface temperatures are particularly important when they are greater than 28°–29°C. In 1965–66, the Canton Island data (Bjerknes, fig. 1, 1969) and figure 5 indicate that such high temperatures were located east of normal, probably in response to the weak equatorial trades and reduced upwelling.

The following year, as the equatorial trades strengthened and ocean temperatures dropped, this mean tropical

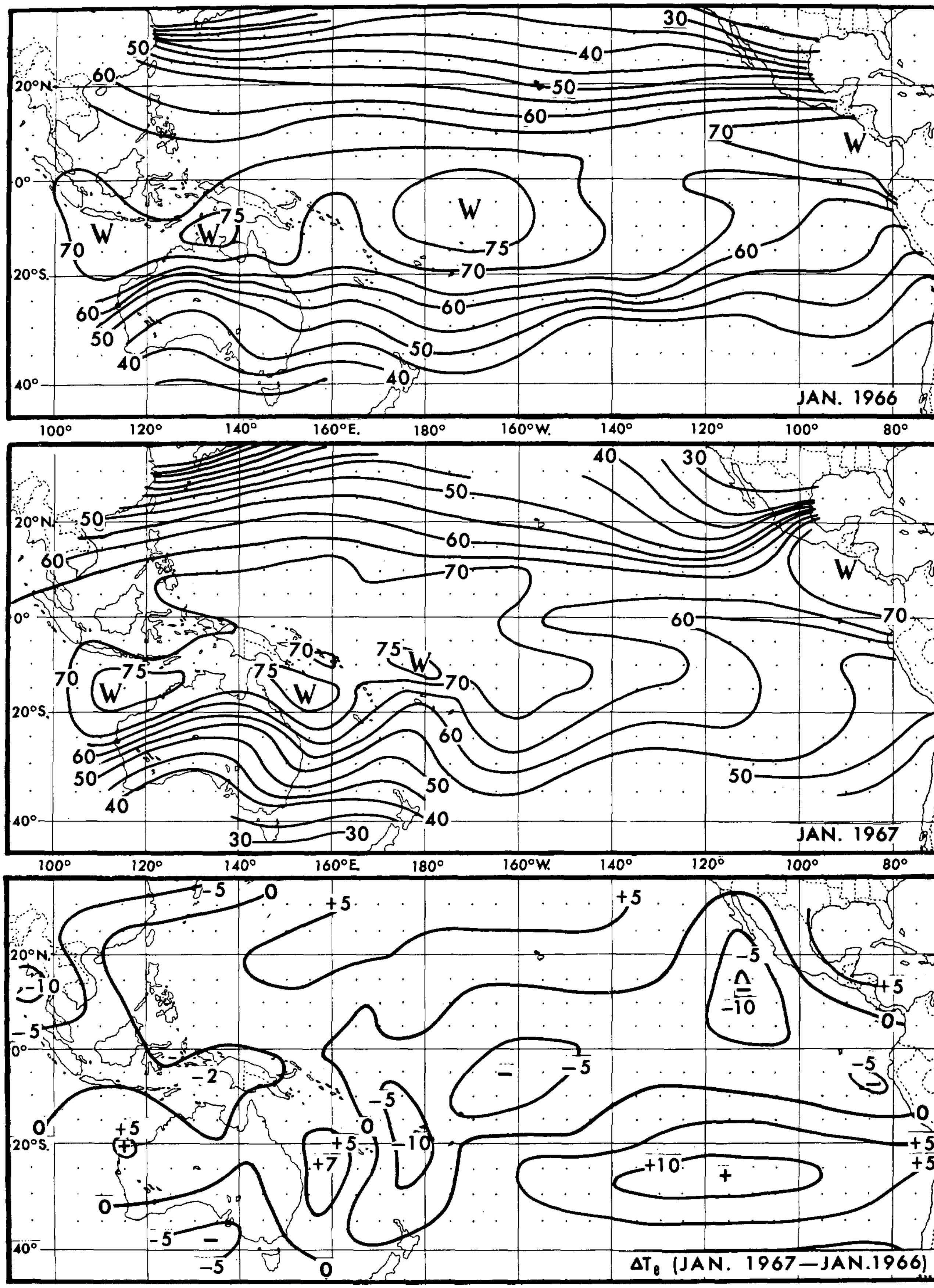

FIGURE 8.—Surface equivalent temperature (degrees Celsius) $T_E = T + (L/c_p)q$ for January 1966 and January 1967. Lower chart is the change in T_E from January 1966 to January 1967.

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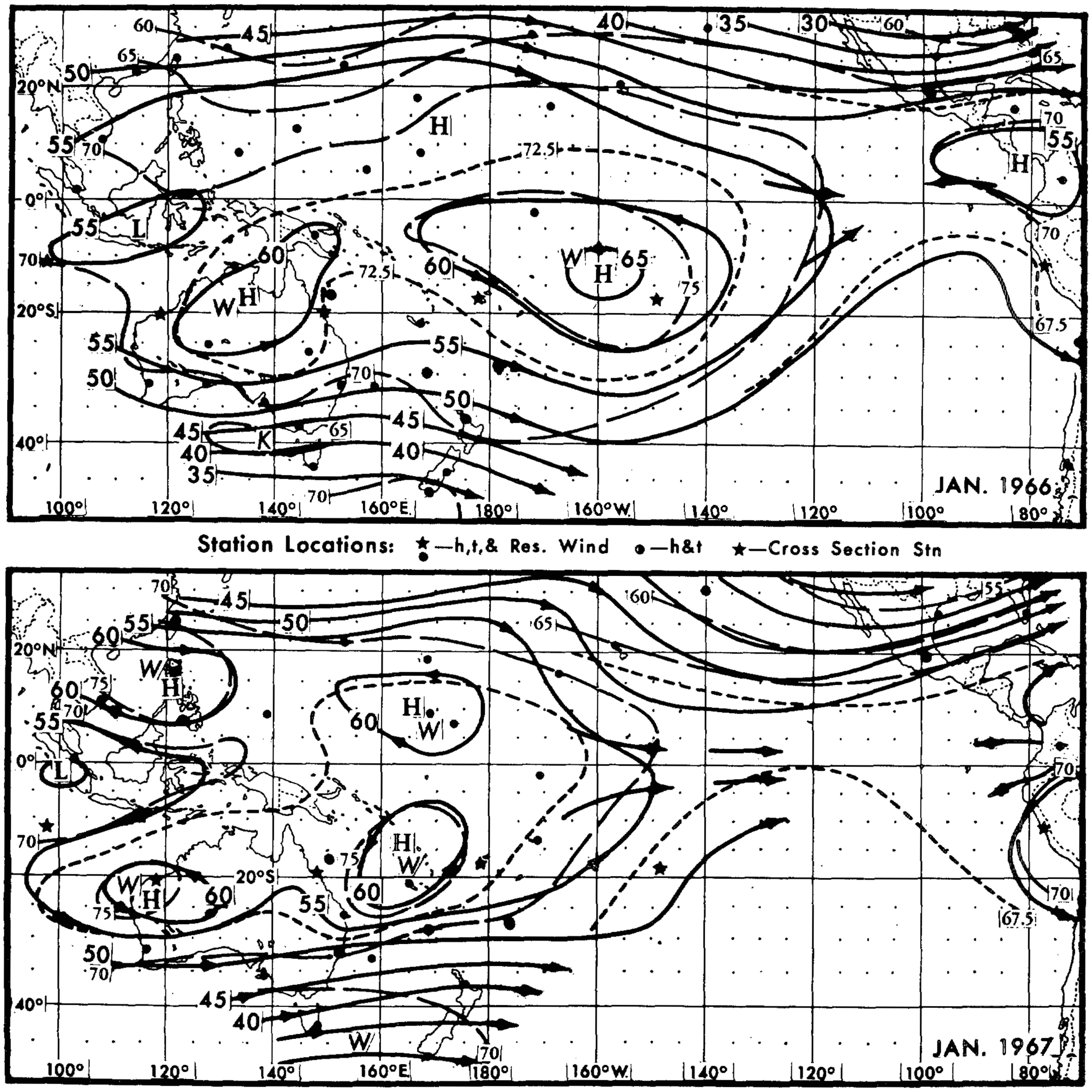

FIGURE 9.—Monthly mean contours for 100 mb (solid) and thickness between 500 mb and 100 mb (dashed) for January 1966 and January 1967. Contours (100 mb) are in decameters minus 1600; thickness contours are in decameters minus 1000. Arrows in the vicinity of the Equator represent the suggested high-level flow.

circulation near Samoa gave way and shifted westward to a position near the Solomon Islands with another center located over northwestern Australia (figs. 7, 9). Again resultant winds, while meager, indicated a warm core and anticyclonic circulation in the upper troposphere.

These energy-producing tropical circulations are integral parts of the equatorial trough zone and, in turn, of the Hadley circulation. As such, they import water vapor, condense it, and export the released latent heat in the upper troposphere. But, as we have seen, satellite cloud observations indicate that there are important longitudinal differences (fig. 6). The extensive cloudiness and heavy rainfall located over Indonesia, New Guinea, and northern Australia and the low amounts of cloud and rainfall east of 180° suggest that the convective systems described previously are part of a large-scale standing eddy that also has a significant part of its circulation in a zonal plane. Figure 10, which is a plot of zonal wind versus pressure at Canton Island, indicates that this circulation was much more intense in January 1967 than during the previous year. The existence of such a thermally direct circulation in a west-east plane has been postulated by Troup (1965). More recently, Bjerknes (1969) has appropriately suggested that it be referred to as the "Walker circulation" because of its relation to the so-called "Southern Oscillation" discovered by Sir Gilbert Walker (1924) (see also Berlage, 1966). Essentially what is meant by the "Southern Oscillation" is an inverse correlation in sea-level pressure between Indonesia and the eastern South Pacific Ocean. Its variation in turn is indicative of longitudinal shifts of the Walker mean zonal circulation.

Zonal variations in equatorial cloudiness are not confined to the Pacific, for there are also important areas of cloudiness over South America and Africa (fig. 11). This suggests that there are three major areas of upward motion in the Tropics, especially during winter, with subsidence in between—or essentially three standing eddies with a significant part of their circulations in a zonal plane. The usual practice of calculating zonal averages so as to isolate the mean meridional circulation tends to obscure these quasi-permanent perturbations of the tropical atmosphere. Undoubtedly, it is the convective heating occurring primarily within these three areas (Ramage, 1968, refers to these areas as "tropical maritime continents") that drives the Hadley circulation. These longitudinal variations of heating and temperature raise the possibility that the eddy generation and conversion of available potential energy may be important in the Tropics—perhaps even more important than the zonal generation. As Asnani (1968) has indicated, the meridional temperature gradient is so weak in the Tropics that the sign of even the zonal energy conversions is uncertain.

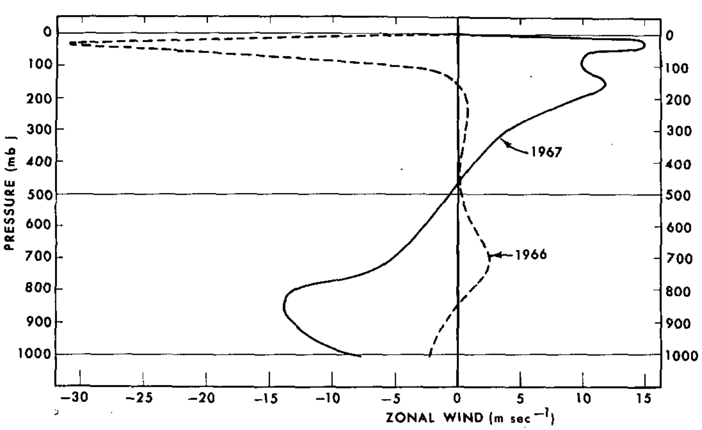

FIGURE 10.—Monthly zonal wind component versus pressure for Canton Island for January 1966 (dashed) and January 1967 (solid).

4. RELATION TO HIGHER LATITUDE CIRCULATIONS

As was indicated in the introduction, Bjerknes suggested that a greater amount of condensation heating in the Tropics should be accompanied by stronger zonal westerlies, and the winter of 1957–58 was cited as an example. Our studies of the equatorial Pacific seem to indicate such a relationship, for the anomalous equatorial circulation during January 1966, with its excess rainfall over the region in the vicinity of Canton Island, was accompanied by unusually strong westerlies south of 40° latitude over the Northern Hemisphere. January 1965 and 1967 (dry at Canton) in contrast experienced weaker westerly flow. This is seen in figure 12, which is a meridional profile of monthly average zonal kinetic energy for the 850- to 500-mb layer. In the Australia-New Zealand sector of the Southern Hemisphere, yearly pressure changes indicate that the westerlies south of 40° were also stronger in January 1966 than in both January 1965 and 1967.

Rather striking is an approximate 2-yr oscillation in the zonal kinetic energy for the Northern Hemisphere, which since 1963 varied in a manner similar to the ocean temperatures and rainfall at Canton Island. In contrast, the eddy kinetic energy varied inversely. This is shown in figure 13, which is a time series of 12-mo running means of the zonal and eddy kinetic energy for the North-

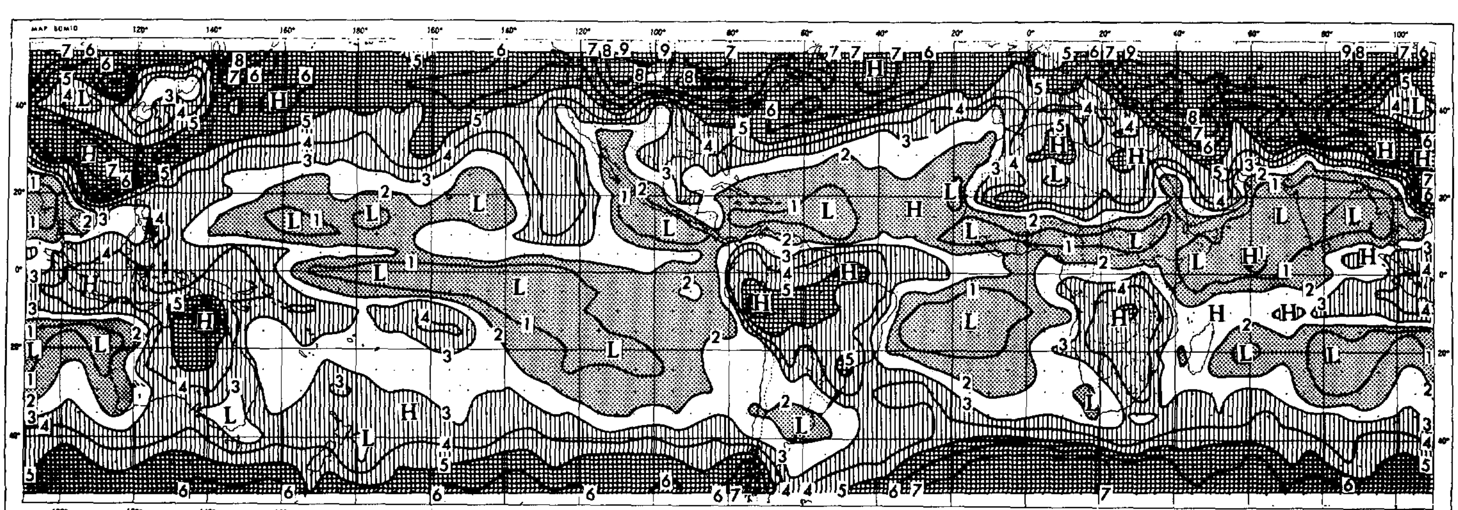

FIGURE 11.—Monthly mean brightness for February 1967 obtained from digitized pictures from ESSA 3. Hatching indicates cloudiness greater than 3, while stippling indicates cloudiness less than 2. Note the rather large longitudinal variation in cloudiness near the Equator.

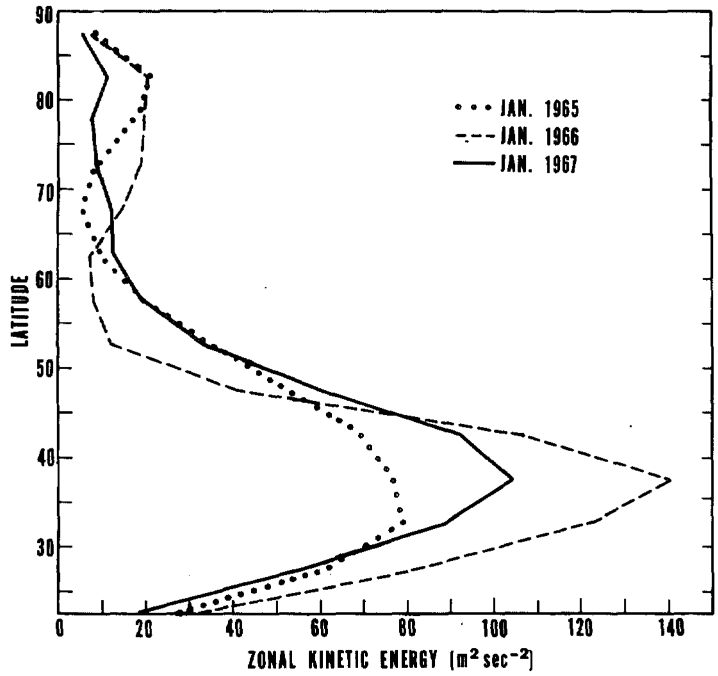

FIGURE 12.—Latitudinal profile of Northern Hemispheric zonal kinetic energy for three successive Januaries. Data are for the layer 850–500 mb.

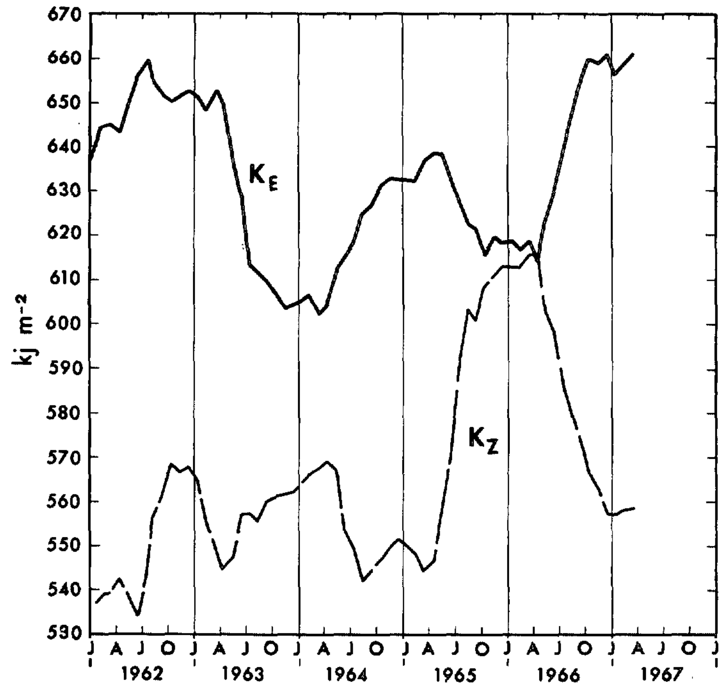

FIGURE 13.—Time series of 12-mo running means of zonal and eddy kinetic energy for the Northern Hemisphere north of 20°. Data are for 850–200 mb and were obtained from objective analysis prepared by the National Meteorological Center.

ern Hemisphere north of 20° latitude and integrated between 850 and 200 mb. The use of 12-mo running means can be viewed as a statistical filtering process applied so as to isolate low-frequency oscillations with periods longer than 1 yr. Since a large part of the eddy kinetic energy is in the long planetary waves, this graph suggests a possible inverse relation between the large-scale standing eddies in the westerlies and those located near the Equator. It also raises a rather fundamental question with regard to the interaction of these perturbations in the westerlies with those in the Tropics.

While the dynamics of these long planetary waves are still not clearly understood, it appears that they arise in response to vertical motions forced by continent-ocean thermal contrasts as well as by the earth's orography (Saltzman, 1965). Consequently, higher latitude energy sources are involved. However, these planetary waves are modified by an interaction with the cyclone scale eddies, which in turn usually supply energy to the mean zonal flow (Saltzman and Fleisher, 1960). Interestingly, this transformation from eddy to zonal kinetic energy was particularly large during the late fall and winter of 1965–1966 (table 1). In addition, there was a tendency during the years 1963–67 for these late fall and early winter values to alternate from year to year in phase with or slightly ahead of the zonal kinetic energy. Quite likely, the strengthening and equatorward shift of the westerlies, particularly in 1965–66, represented a response to these higher latitude energy transformations as well as to those in the Tropics.

If, as Bjerknes has suggested, the Hadley circulation is stronger and exports more heat polewards during the periods of excess equatorial rainfall, then there must also

TABLE 1.—*Monthly averages of the transformation between zonal and eddy kinetic energy for fall and winter months. Negative values indicate a transformation from eddy to zonal kinetic energy. The values are in watts m^{-2} for the area north of latitude 20° N. and are summed between 850 mb and 200 mb.*

	1962–63	1963–64	1964–65	1965–66	1966–67	1967–68
Oct	—	−47	−34	−41	−14	−39
Nov	−32	−43	−30	−62	−23	−22
Dec	−17	−27	− 8	−37	−17	+ 7
Jan	+48	+ 1	−10	−29	− 3	− 7
Feb	+37	+ 1	+ 6	−42	− 3	—

be a larger cooling in subtropical latitudes. This occurs primarily in the winter hemisphere and is a result of nonadiabatic processes, largely radiative. In addition, it is brought about by a large-scale horizontal eddy heat flux that becomes increasingly important poleward of latitudes 15°. Perhaps the intensity and distribution of extratropical heat sources determines the degree to which tropical circulations are coupled with the westerlies. When these heat sources are weak, the Tropics respond with a greater export of heat derived largely from condensation heating. Stronger midlatitude heat sources on the other hand would require a weaker response from the Tropics to maintain a balance. Thus, middle-latitude energy sources can alter the energy flux from the Tropics. It is apparent that much more study must be given to this interaction between the large-scale circulations in the Tropics and the higher latitude westerlies. In this regard, the studies of large-scale air-sea interaction carried out by Namias (1969) are especially interesting.

5. SUMMARY

The temperature of the equatorial eastern Pacific Ocean varies inversely with the strength of the trade winds above. This is a consequence of variations in intensity of the surface wind stress, which regulates the intensity of the upwelling. Sea-surface temperatures above 28°–29°C (probably indicating a cessation of the upwelling) are associated with heavy rainfall as Bjerknes has indicated. But, while high ocean temperatures appear to be necessary for increased tropical convection and the formation of the large-scale stationary circulations that make up the equatorial trough zone, they alone are not sufficient. Satellite observations over the eastern equatorial Pacific usually indicate low amounts of cloudiness, which occur when the ocean surface is warm. These observations suggest widespread subsidence over this region as Riehl has maintained. This subsidence appears to be part of a large-scale, essentially zonal, circulation over the equatorial Pacific that is driven by a release of latent heat normally occurring over Indonesia, New Guinea, and northern Australia, but sometimes occurring as far east as Canton Island. Fluctuations in the intensity of this circulation are essentially a manifestation of Walker's "Southern Oscillation" and are related to the air-sea interaction described above. Particularly intriguing are the very low-frequency variations this circulation exhibits. While these appear to be related to variations in the higher latitude circulations of both hemispheres, the mechanism involved is unclear. If the midlatitude westerlies respond to changes in equatorial circulation as Bjerknes has postulated, how do they in turn influence these equatorial circulations? What role do the long planetary waves in the westerlies play in this interaction? It is hoped that the accumulation of comprehensive data from the Tropics by means of satellite measurements and other observational programs in the next few years will aid in probing these relationships more deeply.

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